

TOPOGRAPHIC CHANGES ON AJIGAURA BEACH TRIGGERED BY ELONGATION OF OFFSHORE BREAKWATER

Y. Noshi¹, T. Uda², M. Serizawa³ and T. Kumada²

ABSTRACT: On Ajigaura Beach in Ibaraki Prefecture, Japan, severe beach erosion has occurred. Despite beach nourishment as a measure against beach erosion, wave run-up damage occurred in the south part of the beach where the foreshore was narrowed. The topographic changes of the beach were investigated on the basis of past aerial photographs and bathymetric survey data, and a numerical simulation using the BG model (a three-dimensional model for predicting beach changes based on Bagnold's concept) was carried out. The measured and calculated results were in good agreement. It was concluded that the beach changes at Ajigaura Beach were triggered by northward longshore sand transport, which was induced by the wave-sheltering effect of the offshore breakwater.

Keywords: Offshore breakwater, wave-shelter zone, beach erosion, Ajigaura beach, longshore sand transport

INTRODUCTION

When a long offshore breakwater is extended, a wave-shelter zone is formed in the lee of the breakwater, and longshore sand transport is induced from outside to inside the breakwater, resulting in beach erosion outside the wave-shelter zone and sand deposition inside it. These beach changes caused by anthropogenic factors have been observed at many places along Japan's coasts (Uda, 2010). Along the Ibaraki coasts, the same phenomena occurred at Oharai Port, resulting in the alteration of a natural sandy beach into an artificial coast covered with a number of concrete blocks (Matsu-ura et al., 2010). The same situation was also observed at Otsu fishing port (Uda, 2010). Even though there are many examples, no improvements have been carried out on Japan's coasts mainly owing to the deficiencies of the social system or the shortcoming of the coastal management separated by a sector-by-sector system. Thus, the same situation has recurrently occurred beyond the scope of engineering. In this study, we consider this issue taking Ajigaura Beach as an example.

Ajigaura Beach is one of the famous bathing beaches in Ibaraki Prefecture. In recent years, severe beach erosion has occurred. Even though beach nourishment has been carried out as a measure against beach erosion, wave run-up damage often occurred in the south part of the beach where the foreshore was narrowed. Yokoki et al. (2003) investigated the recent beach changes using aerial photographs and bathymetric survey data. They showed that the south part of the coast had been eroded since 1998, whereas in the north part, accretion occurred

along with the accumulation of gravel on the foreshore of the eroded beach. They also showed that the beach slope gradually steepened because of erosion and the area with the steep slope gradually moved landward finally for the foot of the seawall to be exposed to waves. Uda (2010) pointed out that the erosion of this beach is closely related to the extension of an offshore breakwater of Hitachinaka Port, which generated northward longshore sand transport from inside to outside the wave-shelter zone. In this study, the shoreline changes between 1984 and 2010 were investigated using aerial photographs as well as the analysis of the bathymetric survey data taken in 1996, 1999, and 2002, and the numerical simulation using the BG model (a three-dimensional model for predicting beach changes based on Bagnold's concept) was carried out to quantitatively reproduce the measured beach changes.

COMPARISON OF AERIAL PHOTOGRAPHS

Ajigaura Beach is located in the central part of Ibaraki Prefecture and faces the Pacific Ocean, as shown in Fig. 1. The beach changes on Ajigaura Beach are closely related to the construction of the offshore breakwater of Hitachinaka Port. This offshore breakwater had been extended southward, resulting in the southward expansion of the wave-shelter zone. Figure 2 shows the aerial photograph taken in 2010 including this offshore breakwater. The offshore breakwater had been extended 2.4 km offshore of Ajigaura Beach in parallel to the coastline. Although the south end of the breakwater was located offshore of the

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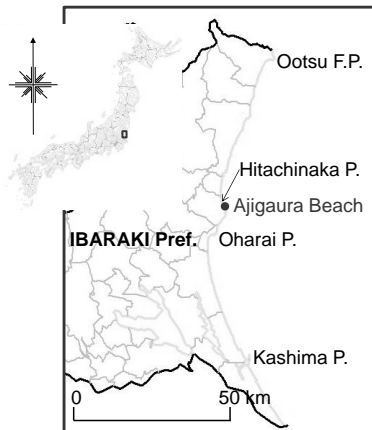


Fig. 1 Location of Ajigaura Beach.

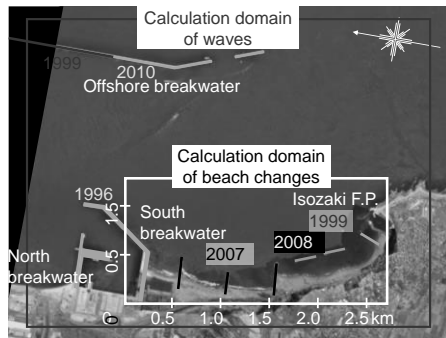


Fig. 2 Construction history of offshore breakwater of Hitachinaka Port and calculation domains.

operation base in 1999, almost half of Ajigaura Beach was enclosed by the offshore breakwater, leaving a 250-m-wide opening until 2010.

Although Ajigaura Beach had been exposed to ocean waves until 1999, almost half of the beach was sheltered by the offshore breakwater until 2002, permitting only oblique wave incidence from SE. This wave direction makes an angle of 55° clockwise to the direction normal to the mean coastline of Ajigaura Beach ($N80^\circ E$), and therefore strong northward longshore sand transport was induced from outside to inside the wave-shelter zone.

Figure 3 shows the aerial photographs of Ajigaura Beach taken between 1984 and 2010. In 1984, a gradually curved shoreline extended in the study area except the vicinity of Isozaki fishing port located at the south end (Fig. 3(a)). In the north part of the study area, natural sand dunes had developed owing to the windblown sand caused by the prevailing wind from NE. Ajigaura Beach was a natural sandy beach at this time without any offshore structures and was a well-known surfing ground.

By 1996, the construction of the breakwaters of the operation base had been completed, as shown in Fig. 3(b). At Isozaki fishing port, the east breakwater was extended northward by 120 m compared with that in 1984 and a jetty with a length of 200 m was newly extended 100 m north of the west breakwater. Because

the jetty was extended after the deposition of sand in the wave-shelter zone formed by the extension of the east breakwater of Isozaki fishing port, sand was enclosed between the jetty and the west breakwater, losing mobility as active littoral sand. As a result, the shoreline receded in the central part of Ajigaura Beach owing to the sand movement toward both ends of the study area.

By 2009, beach nourishment using $4.0 \times 10^5 \text{ m}^3$ of sand had been carried out along with the construction of three groins and two detached breakwaters as measures against beach erosion (Fig. 3(c)). Finally, a natural sandy beach disappeared in Ajigaura owing to the construction of these structures and was reduced to an artificial pocket beach surrounded by many coastal structures, although the beach width was significantly widened compared with that in 1999 owing to the beach nourishment. After the beach nourishment and construction of the detached breakwaters, cusped forelands were formed behind the detached breakwaters, as shown in Fig. 3(c). However, their sizes decreased by 2010 (Fig. 3(d)) and the stepped shoreline was formed by the blockage by the groins.

In what follows, the shoreline configuration was read from these aerial photographs and their changes were calculated for the validation of the BG model. The correction of the shoreline position was made using the foreshore slope of $1/12$ measured on January 23, 2011 and the tide level when photographs were taken. For the analysis, the X - and Y -axes were adopted alongshore and normal to the X -axis, as shown in Fig. 3, and the offshore distance from the X -axis to the shoreline was read, except the vicinity of Isozaki fishing port, because the shoreline curvature significantly changes there. Here, another coordinate was adopted as shown in Fig. 3.

NUMERICAL MODEL

The BG model (a 3-D model for predicting beach changes based on Bagnold's concept) considering changes in grain size proposed by Serizawa et al. (2007) with some improvements was applied to predict the beach changes. This model can predict not only beach changes, but also grain size changes on a coast composed of sand of mixed grain size. We use Cartesian coordinates (x, y) , where the x - and y -axes are taken in the cross-shore (shoreward positive) and longshore directions, respectively, and consider that the elevation at point $Z(x, y, t)$ is a variable to be solved, where t is time.

N is set to be the number of grain sizes, and introducing the concept of the exchange layer in the same manner as Hirano (1971), denoting $d^{(k)}$ ($k=1, 2, \dots, N$) as a typical grain size of the grain size population in the exchange layer, the content of each

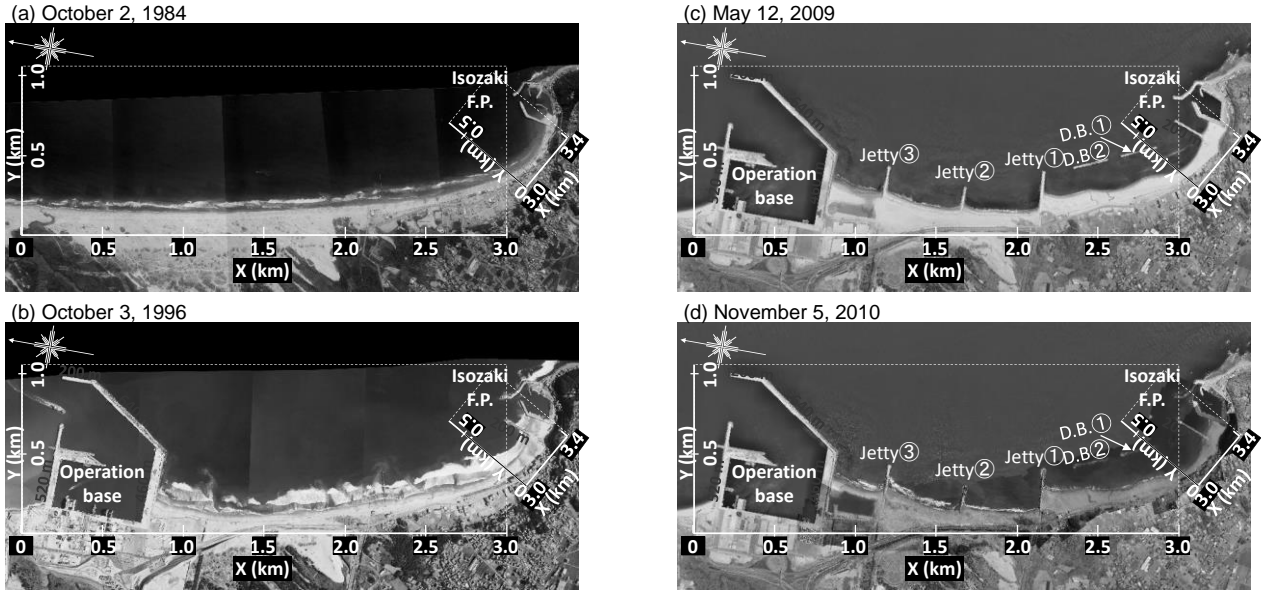


Fig. 3 Aerial photographs of Ajigaura Beach taken between 1984 and 2010.

grain size population (k) in the exchange layer of sand $\mu^{(k)}(x, y, t)$ is added as a variable to be solved.

The beach changes are assumed to occur between the depth of closure h_c and the berm height h_R . The fundamental equations are given by Eqs. (1) - (11).

Sand transport

$$q_x^{(k)} = \frac{G_x^{(k)}}{\tan \hat{\beta}_c^{(k)}} \left[\tan \hat{\beta}_c^{(k)} \cos \theta_w - \partial Z / \partial x \right] \quad (1a)$$

$$; k = 1, 2, \dots, N$$

$$q_y^{(k)} = \frac{G_y^{(k)}}{\tan \hat{\beta}_c^{(k)}} \bullet$$

$$\left[\tan \hat{\beta}_c^{(k)} \left(\sin \theta_w - \frac{1}{\tan \bar{\beta}} \frac{K_2^{(k)}}{K_y^{(k)}} \frac{\partial H_b}{\partial y} \right) - \partial Z / \partial y \right] \quad (1b)$$

$$; k = 1, 2, \dots, N$$

$$G_x^{(k)} = K_x^{(k)} G^{(k)} ; k = 1, 2, \dots, N \quad (2a)$$

$$G_y^{(k)} = K_y^{(k)} G^{(k)} ; k = 1, 2, \dots, N \quad (2b)$$

$$G^{(k)} = \mu^{(k)} C_0 \varepsilon(Z) \left(EC_g \right)_b \cos^2 \alpha_b \tan \bar{\beta} \quad (3)$$

$$; k = 1, 2, \dots, N$$

$$K_y^{(k)} = \frac{A}{\sqrt{d^{(k)}}} ; k = 1, 2, \dots, N \quad (4)$$

$$\tan \hat{\beta}_c^{(k)} = r \cdot \tan \beta_c^{(k)} + (1-r) \cdot \tan \bar{\beta}_c \quad (5)$$

$$(0 \leq r \leq 1); k = 1, 2, \dots, N$$

$$\ln [\tan \bar{\beta}_c] = \sum_{k=1}^N \left\{ \mu^{(k)} \ln [\tan \beta_c^{(k)}] \right\} \quad (6)$$

$$\int_{-h_c}^{h_R} \varepsilon(Z) dZ = 1 \quad (7)$$

$$\varepsilon(Z) = \begin{cases} \frac{1}{h_c + h_R} & (-h_c \leq Z \leq h_R) \\ 0 & (Z < -h_c, h_R < Z) \end{cases} \quad (8)$$

Mass conservation for each grain size

$$\frac{\partial Z^{(k)}}{\partial t} = - \frac{\partial q_x^{(k)}}{\partial x} - \frac{\partial q_y^{(k)}}{\partial y} ; k = 1, 2, \dots, N \quad (9)$$

Change in seabed elevation

$$\frac{\partial Z}{\partial t} = \sum_{k=1}^N \frac{\partial Z^{(k)}}{\partial t} \quad (10)$$

Change in content of each grain size population

$$\frac{\partial \mu^{(k)}}{\partial t} = \begin{cases} \frac{1}{B_h} \left(\frac{\partial Z^{(k)}}{\partial t} - \mu^{(k)} \frac{\partial Z}{\partial t} \right) & \frac{\partial Z}{\partial t} \geq 0 \\ \frac{1}{B_h} \left(\frac{\partial Z^{(k)}}{\partial t} - \mu_B^{(k)} \frac{\partial Z}{\partial t} \right) & \frac{\partial Z}{\partial t} < 0 \end{cases} \quad (11)$$

$$; k = 1, 2, \dots, N$$

Here, (x, y) are the Cartesian coordinates; the x - and y -axes are taken in the cross-shore (shoreward positive) and longshore directions, respectively. $q_x^{(k)}$ and $q_y^{(k)}$ are the x - and y -components of sand transport flux for each grain size population (k) in the exchange layer of sand, N is the number of grain sizes, and $\mu^{(k)}(x, y, t)$ is the volume content of each grain size population (k) in the exchange layer of sand. $Z(x, y, t)$ is the seabed elevation with reference to the still water level ($Z = 0$), θ_w is the angle of wave propagation measured counterclockwise to the direction of the x -axis, $\tan \hat{\beta}_c^{(k)}$ is the equilibrium slope of sand of each grain size for sand composed of mixed grain sizes, and $\tan \beta_c^{(k)}$ is the

equilibrium beach slope of each grain size population (k). The beach slope in the surf zone $\tan \bar{\beta}$ was given by the initial seabed slope. $K_x^{(k)}$ and $K_y^{(k)}$ are the coefficients of cross-shore and longshore sand transport, respectively, $K_2^{(k)}$ is the coefficient of the term given by Ozasa and Brampton (1980), H_b is the breaker height, $(EC_g)_b$ is the energy flux at the breaking point, α_b is the breaker angle, and $d^{(k)}$ is a typical grain size of the grain size population. A is a coefficient that depends on the physical conditions of the beach, $d^{(k)}$ in Eq. (4) has a unit of mm, $\varepsilon(Z)$ is the depth distribution of the intensity of longshore and cross-shore sand transport, and a uniform distribution as in Eq. (8) is assumed for the integral of over the depth zone between $-h_C$ and h_R to be equal to 1 (Eq. (7)). C_0 is the coefficient transforming the immersed weight expression into a volumetric expression ($C_0 = 1/\{(\rho_s - \rho)g(1-p)\}$), where ρ is the density of seawater, ρ_s is the specific gravity of sand particles, p is the porosity of sand and g is the acceleration due to gravity). h_C is the depth of closure and h_R is the berm height. In addition, $\mu_B^{(k)}$ is the content of each grain size population on the sandy beach landward of the initial exchange layer. B_h is the thickness of the exchange layer.

The sand transport equation Eq. (1) is expressed using the wave energy at the breaking point, similar to the BG model (Serizawa et al., 2007), with several improvements, and the variables in Eq. (1) were given by Eqs. (2) - (8). First, both longshore and cross-shore sand transport coefficients $K_y^{(k)}$ and $K_x^{(k)}$ are included. In addition, an additional term given by Ozasa and Brampton (1980) was incorporated into the fundamental equation of the BG model to evaluate the longshore sand transport due to the effect of the longshore gradient of breaker wave height. Assuming $K_x^{(k)} = K_y^{(k)}$ and neglecting the additional term given by Ozasa and Brampton, this equation coincides with the sand transport equation by Serizawa et al. (2007).

The equilibrium slope was calculated from the weighted average of the equilibrium slope of each grain size $\tan \beta_c^{(k)}$ and the local slope corresponding to the grain size component $\tan \bar{\beta}_c$ after Noshi et al. (2006). When we assume $r = 1$ in Eq. (5), the equation becomes equal to the equation in the BG model (Serizawa et al., 2007). In this study, r was assumed to be 0.5.

The calculation domain was discretized in 2-D elements with the widths Δx and Δy . The calculation points of the seabed elevation Z and sand transport rate $\vec{q}^{(k)} = (q_x^{(k)}, q_y^{(k)})$ were distributed using the staggered meshes with a half mesh interval, and the equations were solved by the explicit finite difference method. In addition, the point calculating the content of each grain size population $\mu^{(k)}$ is placed at the same location as that of the calculation point Z .

Given the initial bathymetry and initial distribution of $\mu^{(k)}$ and $\mu_B^{(k)}$, H_b , θ_w , α_b , h_C , h_R and the equilibrium beach slope of each grain size population, sand transport fluxes of $\vec{q}^{(k)} = (q_x^{(k)}, q_y^{(k)})$ can be calculated from Eq. (1). Furthermore, the depth changes of all the grain size populations are determined from Eq. (9), and the depth changes after Δt are determined from Eq. (10) from the summation of the depth changes of all the grain size populations at that position. In addition, the change in $\mu^{(k)}$ after Δt is determined using Eq. (11). These calculations were recurrently carried out. For the boundary conditions, sand transport was set to be 0 at the solid boundary. In calculating Eq. (3), $\mu^{(k)}$ at the calculation point of Z located upcoast of the calculation point of sand transport was used.

In estimating the intensity of sand transport near the berm top and at the depth of closure, the intensity of sand transport was linearly reduced to 0 near the berm height or the depth of closure to prevent sand from being deposited in the zone higher than the berm height and the beach from being eroded in the zone deeper than the depth of closure, similarly to that in Serizawa et al. (2003).

CHANGE IN WAVE FIELD ASSOCIATED WITH EXTENSION OF PORT BREAKWATER

Table 1 shows the energy-mean significant wave height, wave period and their probabilities for each wave direction calculated from the wave observation data (NOWPHAS) measured between January 1980 and November 1997 offshore of Hitachinaka Port. The probabilities of the wave direction on Ajigaura Beach over a year are 38.2% (E), 30.2% (ENE) and 20.6% (ESE), and the probability of all three directions is 88.9%. The energy-mean significant wave height over a year is 1.32 m ($T = 8.4$ s), and the predominant wave direction was N80°E.

Table 1 Wave characteristics measured between January 1980 and November 1997 off Hitachinaka Port.

Wave direction	Significant wave height (m)	Wave period (s)	Probability (%)
NE	1.36	8.9	8.2
ENE	1.35	8.7	30.2
E	1.28	8.3	38.2
ESE	1.27	8.2	20.6
SE	1.38	7.6	2.8

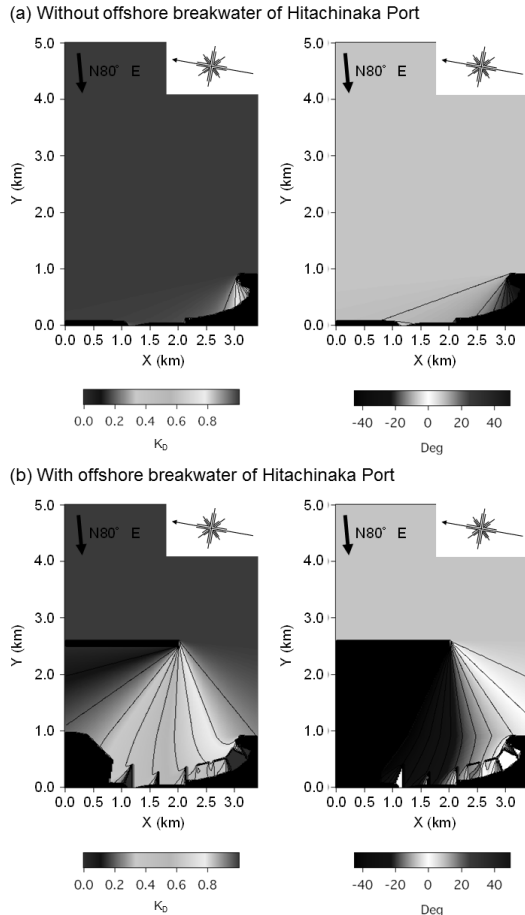


Fig. 4 Distribution of wave diffraction coefficient K_D and wave direction with/without offshore breakwater of Hitachinaka Port.

In the calculation of wave field, the energy-mean wave as mentioned above was selected as the incident waves, and diffraction waves were calculated using the angular spreading method for irregular waves (Sakai et al., 2006). The calculation domain was divided by the mesh intervals of 10 m. For the incident wave conditions, the energy-mean wave height of $H_0 = 1.32$ m ($T = 8.4$ s) and wave angle $\alpha = N80^\circ E$ were adopted. Then, the wave field was calculated under the conditions with/without the offshore breakwater of Hitachinaka Port, and the conditions of the coastal structures in 1984 and 2010 were considered. The mean sea level was selected and the directional spreading parameter S_{max} was assumed to be 75.

Table 2 Calculation conditions.

Calculation method	BG model (Serizawa et al., 2007) considering changes in grain size with some improvements Angular spreading method for irregular waves (Sakai et al., 2006)
Calculation domain	Operation base to Isozaki fishing port on Ajigaura Beach
Years of reproduction calculation	1996, 1999 and 2010
Initial bathymetries	Reproduced bathymetry in 1984 for calculation in 1996 Reproduced bathymetry in 1996 for calculation in 1999 Reproduced bathymetry in 1999 for calculation in 2010
Grain sizes and content	0.1 mm (30%) and 0.425 mm (70%)
Equilibrium slope and grain size of sand	1/80 ($d = 0.1$ mm) 1/12 ($d = 0.425$ mm)
Incident wave conditions	Wave height $H_0 = 1.32$ m and wave direction 0 degrees ($N80^\circ E$)
Tide level	Mean sea level
Range of beach changes	Between berm height $h_R = 3.0$ m and depth of closure $h_C = 7.0$ m
Boundary conditions	Solid boundary at both ends
Coefficient of sand transport	$A = 0.3$ Ratio between cross-shore and longshore sand transport: $K_x^{(1)} / K_y^{(1)} = 0.1$ Ozasa and Brampton (1980)'s coefficient: $K_x^{(1)} / K_y^{(1)} = 1.62$
Depth distribution of sand transport	Uniform in depth
Critical slope	1/2 on land and 1/3 on seabed
Calculation domain	$X = 500 - 3400$ m and $Y = 0 - 1200$ m
Mesh size	$\Delta X = 20$ m and $\Delta Y = 10$ m
Time intervals	$\Delta t = 1$ hr
Correspondence of calculation time to real time	1 year = 8760 steps
Numerical simulation method	Explicit finite difference method

Figure 4(a) shows the distribution of wave diffraction coefficient (K_D) and wave direction without the offshore breakwater of Hitachinaka Port. Before the construction of the offshore breakwater, the entire coastline was exposed to ocean waves except the vicinity of Isozaki fishing port, where a wave-shelter zone was locally formed by the fishing port breakwater. After the extension of the offshore breakwater, a large-scale wave-shelter zone was formed in the lee of the offshore breakwater and extended between the operation base and Isozaki fishing port. In particular, the wave direction has changed from the direction normal to the shoreline to that of waves obliquely incident from the clockwise direction with a large angle.

CALCULATION CONDITIONS FOR BEACH CHANGES

In the study area, the wave field has markedly changed associated with the extension of the offshore breakwater of Hitachinaka Port, and thus, the calculation domains for the wave field and beach changes were separately adopted so that the wave diffraction effect of the offshore breakwater can be taken into account. In the calculation using the BG model considering changes in grain size, beach changes between the berm height of $h_R = 3.0$ m and the depth of closure of $h_C = 7.0$ m were calculated. In the calculation of beach changes, the topography in 1984 before erosion was assumed to be the initial topography from which the reproduction calculation was carried out. In this case, only the shoreline configuration was measured in 1984 without a full-scale measurement of the offshore bathymetry. Therefore, the bathymetry in 1984 before erosion was

produced from the measured shoreline position, assuming that the contours extended in parallel to the shoreline with the mean offshore slope of 1/80 and the mean foreshore slope of 1/12, which were determined from the bathymetric survey data in 2002. The waves as mentioned above were assumed to be incident to this produced initial bathymetry for 10 years, and the obtained beach topography was regarded as the initial topography in 1984. Since the port breakwaters had been gradually extended over time, the structural conditions were reset each time in accordance with the construction history of the structures. Other calculation conditions are shown in Table 2.

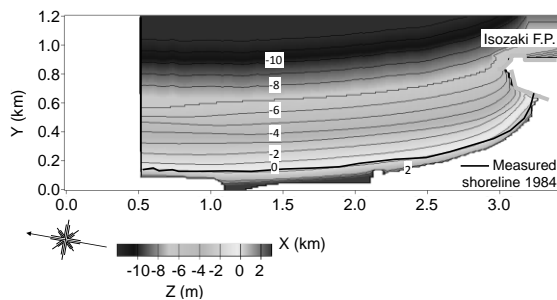


Fig. 5 Calculated bathymetry and measured shoreline configuration in 1984.

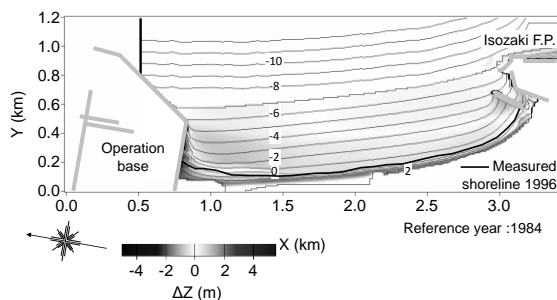


Fig. 6 Reproduced bathymetry in 1996 and bathymetric changes until 1996 with reference to that in 1984.

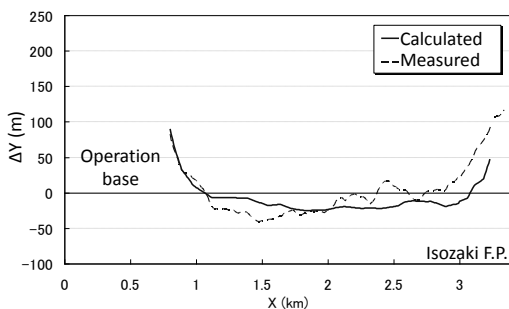


Fig. 7 Calculated shoreline changes until 1996 with reference to that in 1984.

RESULTS

Although the numerical calculation was carried out using Cartesian coordinates (x , y), in which the x - and y -

axes are taken in the cross-shore (shoreward positive) and longshore directions, respectively, the results are easy to understand when the x -axis is exchanged with the y -axis and we adopt the cross-shore coordinate being seaward positive. We define Cartesian coordinates (X , Y), in which the X - and Y -axes are taken in the longshore and cross-shore (seaward positive) directions, respectively.

Figure 5 shows the calculated bathymetry in 1984 using these coordinates (X , Y) along with the measured shoreline configuration in 1984 under the conditions as mentioned above. The measured and calculated shoreline configurations are in good agreement in Fig. 5, and this bathymetry has reached a stable form without any bathymetric changes despite further wave action. Therefore, the bathymetry shown in Fig. 5 was adopted as the initial bathymetry for the calculation.

Figure 6 shows the reproduced bathymetry in 1996 when the breakwater of the operation base and a jetty of Isozaki fishing port were constructed in the north and south ends, respectively. It is clear that longshore sand transport was induced toward the wave-shelter zone behind these structures, resulting in the deposition in the vicinity of the south breakwater of the operation base and the jetty of Isozaki fishing port. In contrast, the erosion zone extended offshore of the shoreline, particularly in a zone shallower than -7 m immediately south of the breakwater of the operation base. Figure 7 shows the measured and calculated shoreline changes in

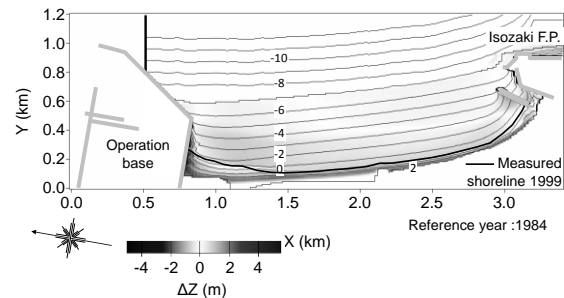


Fig. 8 Reproduced bathymetry in 1999 and bathymetric changes until 1996 with reference to that in 1984.

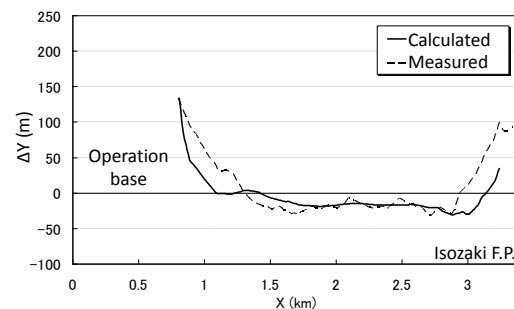


Fig. 9 Calculated shoreline changes until 1999 with reference to that in 1984.

1996 with reference to that in 1984. The calculated shoreline changes were slightly underestimated in the shoreline recession in the south part of the study area, whereas both results are in good agreement near the operation base in terms of the shoreline advance in the north part and the shoreline recession in the central part.

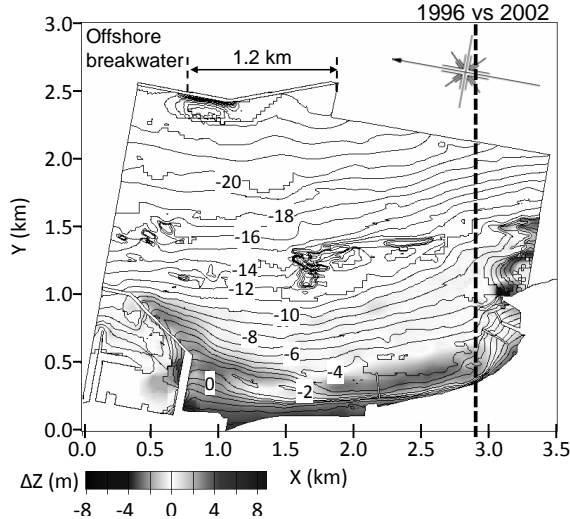


Fig. 10 Bathymetry in 2002 and bathymetric changes until 2002 with reference to that in 1996.

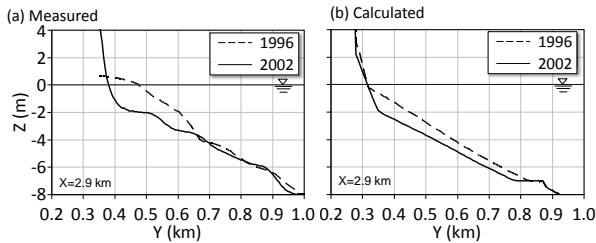


Fig. 11 Profile changes between 1996 and 2002 along transect $X = 2.9$ km.

Figure 8 shows the results of the reproduction calculation of bathymetric changes until 1999. The offshore breakwater of Hitachinaka Port had been extended up to a location offshore of the operation base by 1999, as shown in Fig. 2, resulting in the southward expansion of the wave-shelter zone. As a result, the balance of longshore sand transport was lost, and northward longshore sand transport was newly induced, causing sand deposition in the vicinity of the breakwater of the operation base. Figure 9 shows the measured and calculated shoreline changes up to 1999 with reference to that in 1984. Although the shoreline advance was slightly underestimated, the measured and predicted shoreline advance near the operation base and Isozaki fishing port and the shoreline recession in the central part of the study area agree with each other.

To clearly understand the severe erosion at Ajigaura Beach up to 2002 (Yokoki et al., 2003), the bathymetry in 2002 and bathymetric changes until 2002 with reference to that in 1996 are shown in Fig. 10, where

blue (red) zone corresponds to the eroded (accretion) area. The southern half of Ajigaura Beach was severely eroded in a depth zone shallower than -6 m, whereas the sand was transported and deposited along the south breakwater of the operation base, forming protruding contours near the south breakwater. These bathymetric changes clearly show the occurrence of northward longshore sand transport flowing from outside to inside the wave-shelter zone of the offshore breakwater.

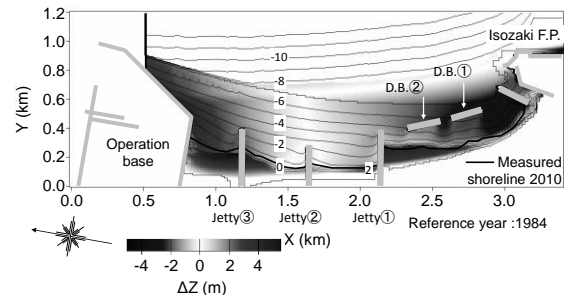


Fig. 12 Reproduced bathymetry in 2010 and bathymetric changes until 1996 with reference to that in 1984.

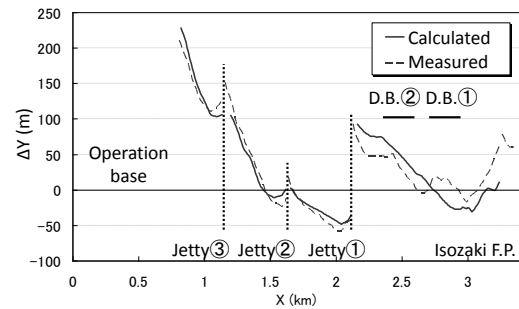


Fig. 13 Calculated shoreline changes until 2010 with reference to that in 1984.

The measured and calculated profile changes along transect of $X = 2.9$ km, as shown by the dotted line in Fig. 10, where the beach width was most narrowed, are shown in Fig. 11. In 1996 before the erosion, the beach slope was as gentle as $1/80$ near the shoreline, but the beach was eroded and the foreshore slope as steep as $1/12$ was formed up to a depth of -2 m leaving a flat slope between 2 and 4 m depth. In calculation, beach erosion occurred between the shoreline and a depth of 7 m deeper than that of the measured changes. Thus, although there are some discrepancies between the measured and predicted profile changes, overall topographic changes were mostly reproduced.

Figure 12 shows the results of the reproduction calculation of beach changes until 2010 when coastal structures such as groins and detached breakwaters were constructed as measures along with the beach nourishment using 4.0×10^5 m³ of sand on Ajigaura Beach. The offshore breakwater of Hitachinaka Port was further extended by 2010, as shown in Fig. 2, and groins 1 - 3 and detached breakwaters 1 and 2 were constructed.

The nourishment sand was mainly composed of well-sorted fine sand because of sand deposited immediately south of the south breakwater of the operation base, which was originally transported by northward sand transport. In the calculation, on the basis of the composition of the bed material sampled in November 2010 from the shoreline at $X = 1$ km near the operation base, the ratio of the content of fine sand ($d = 0.1$ mm) to that of medium-size sand ($d = 0.425$ mm) was set to be 7:3.

Figure 12 clearly shows that as a result of the extension of the offshore breakwater of Hitachinaka Port, a large wave-shelter zone was formed, and northward longshore sand transport was induced toward the wave-shelter zone, resulting in erosion in the south part and accretion in the north part. Furthermore, nourishment sand was mostly composed of fine sand; a large part of the nourishment sand was transported northward turning around the tip of the groin 1.

The appropriateness of the results shown in Fig. 12 was not investigated because of the lack of bathymetric survey data in 2010. Instead, they were compared with the beach changes during the period between 1996 and 2002 when marked beach changes were observed in the absence of any artificial structures, as shown in Fig. 10. In Fig. 10, the beach was eroded in a zone shallower than -6 m in the southern half of Ajigaura Beach, and eroded sand was transported northward depositing along the south breakwater of the operation base. As a result, the contours up to -10 m depth advanced along the breakwater. These observed characteristics are in good agreement with those predicted as shown in Fig. 12.

Figure 13 shows the measured and calculated shoreline changes in 2010. The measured and calculated shoreline changes are in good agreement. Furthermore, the narrowness of the beach width near $X = 3$ km, which causes high wave run-up to the backyard, is also predicted well. In addition, calculation results well explain the fact that beach erosion in the south part of Ajigaura Beach since 1998 and sand deposition in the north part shown by Yokoki et al. (2003) were triggered by the construction of the offshore breakwater of Hitachinaka Port. Furthermore, the piling-up of a large amount of gravel on the foreshore in the erosion zone, which occurred in 2002, can be explained by the mechanism that a sandy beach of a gentle slope mainly composed of fine sand was eroded, resulting in the steepening of the beach slope, and gravel exposed on the seabed was transported shoreward.

CONCLUSION

When a long offshore breakwater is extended, a wave-shelter zone is formed in the lee of the breakwater,

and longshore sand transport is induced from outside to inside the breakwater, resulting in beach erosion outside the wave-shelter zone and sand deposition inside the wave-shelter zone. These beach changes caused by anthropogenic factors have been observed at many places along Japan's coasts (Uda, 2010). The beach changes at Ajigaura Beach can be exactly explained by this mechanism; a wave-shelter zone was formed by the extension of the breakwater of Hitachinaka Port, and longshore sand transport toward the wave-shelter zone formed in the north part of the study area was newly induced, resulting in erosion in the south part and deposition in the north part. Because sand movement occurs in a zone shallower than the depth of closure of $h_C = 7$ m at this coast, northward longshore sand transport was not stopped despite the construction of groins and detached breakwaters constructed in a zone shallower than h_C . Furthermore, although beach nourishment using 4.0×10^5 m³ of sand was also carried out as a countermeasure, a large part of the nourishment sand was transported northward while passing through the offshore of the groin, because the nourishment sand was mainly composed of fine sand. In this study, these beach changes were successfully reproduced using the BG model.

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